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A Methodology for Regional Estimation of Evapotranspiration and irrigation Water Requirements in Center Pivot irrigation Schemes – a case Study in Al-Busaytaa, Northern Saudi Arabia

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Abstract

The implementation of center pivot irrigation systems in desert environment has encountered a harmful effect on the non-renewable ground resources of the Kingdom of Saudi Arabia. It has been recognized that the implementation of the regional water conservation plans for center pivot irrigation is required for sustainable agriculture in Saudi Arabia.. This work illustrates a new methodology for estimating the irrigation water requirements for center pivot irrigated agriculture in a regional scale. The technique merge irrigation water requirements, scheduling techniques, crop identification and the spatial distribution of center pivots in a water resources management frame. The developed method was applied to Al-Busayta irrigation scheme Northen Saudi Arabia The irrigated crops and their relevant acreages were identified using the Landsat image data. Corrcedtion and redesign of irrigation water requirements is performed for the whole crop patterns in the irrigation. The monthly quantity of discharges required for crop water requirements are estimated and compared with well discharge. When the demand discharges of crop are more than the well supplied discharges then irrigated area is calculated to balance the supply and demand. The irrigated area of the center pivot has to be reducing for peak season calculated area. The crop demand discharges relationship is revised according to the estimated irrigated area. The monthly center pivot operation time is estimated as per crop water demands. Using this method, almost a full control on the ground water delivery for irrigation is performed . The applied method has resulted in enormous water saving of 35%. The developed methodology is of a great assistance to the water resources specialists and governmental agencies to monitor water delivery for irrigation.

Introduction

The limited irrigation water resources and the complexity of climate factors in the kingdom of Saudi Arabia, irrigated agriculture depend exclusively on ground water; which is non-renewable fossil water of 10 to 28K Y.B.P age (Edgell, 1997) consuming almost 80 - 90 % of the total water consumption in the Kingdom (Sadik and Barghouti, 1994).). However, the demand for groundwater for center pivot irrigation is intensifying because of the persistent expansion of irrigated soils under the condition of high evapo-transpiration rate and low irrigation efficiencies. This could result in 25% depletion of the ground water reserves by 2010 A.D. (Al Alawi and Abdulrazzak, 1994). The need for regional water conservation mechanism is becoming significant in the assessment of the of water conservation programs in arid regions. The estimation of the regional irrigation requirements based on direct communication with farm owners and field surveys is hard to accomplish. The regional irrigation water consumption system could be generated by utilizing both irrigation water requirement regimes and remotely sensed satellite data. In order to estimate the regional irrigation water requirement, the agriculture acreage and crop types are identified. Since the center pivots are scattered over large areas. These tools have been utilized for supporting the decision-making process in the irrigation water management of large regions. Azzali *et al.,* (1991) stated that the spread of modeling programs utilizing distributed parameters has principally applied the use of input data from remote sensing for controlling large sets of input data. Therefore, this research explains a new methodology of using agro meteorological data for approximately calculating the regional irrigation water requirements, together with remotely sensed data for center pivot irrigation systems. It is expected that the developed work will promote efficient irrigation management practices for sustainable agriculture in arid ecosystem.

Methodology

The estimation of regional irrigation water requirements is carried out as follows:

The crop (i) water requirement (Etc) of any particular crop (i) grown in any particular center pivot (k) could be calculated on monthly or growth stage wise (j) bases (Doorenbos and Pruitt, 1977) as follows:

$$ETc_{(i,j)} = ETo_{(j)} \cdot kc_{(i,j)} \tag{1}$$

Where,

i = Denotes crop type.

j = A delimiter indicating monthly or growth stage wise estimates of reference crop evapotranspiration. i.e 1 to 12 for monthly estimates and 1 to 4 for growth stage wise estimates.

$ETc_{(i,j)}$ = Actual crop (i) evapotranspiration (mm/day) grown in center pivot (*k*).
$ET_{O\ (j)}$ = Average reference crop evapotranspiration (mm/day), in any month or growth stage (j).
$kc_{\ (i\ ,j)}$ = Crop factor for crop type (i) at any particular month or growth stage (j).

The Penman-Monteith technique to estimate crop evapotranspiration (ETo) (Allen et al., 1998):

$$ETo_{(j)} = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2)$$

Where,
$ETo_{(j)}$ = Reference crop evapotranspiration [mm/day] in any month or growth stage (j).
R_n = Net radiation at the crop surface. [MJ/m^2/day]
G = Soil heat flux density. [MJ/m^2/day]
T = Mean daily air temperature at 2 m height. [°C]
u_2 = Wind speed at 2 m height. [m/s]
e_s = Saturation vapour pressure. [kPa]
e_a = Actual vapour pressure. [kPa]
e_s - e_a = Saturation vapour pressure deficit. [kPa],
Δ = The slope of the saturation water vapour pressure – temperature curve. [kPa °C^{-1}]
γ = Psychrometric constant. [kPa °C^{-1}]

The Food and Agriculture Organization (FAO) formulae for calculating the leaching fraction (LF) for center pivot irrigation (Ayers and Westcott, 1985) could be modified to include any particular crop type (i) grown with well *(k)* as follows:

$$LF_{(i,k)} = \frac{ECw_{(k)}}{2 \cdot MaxECe_{(i)}} \cdot \frac{1}{LE} \qquad (3)$$

Where
ECw (k) = The electrical Conductivity of any particular well (mmhos/cm) in the irrigation scheme, serving center pivot (k)
MaxECe (i) = the max. Crop tolerance level for crop (i) (mmhos/cm)
LE = Leaching efficiency (%).

It follows that, the Doorenbos and Pruitt (1977) technique for estimating the irrigation water requirements could be adapted as follows;

$$CWR_{(i,j,k)} = ET_{C(i,j)} \times \left(\frac{1 + LF_{(i,k)}}{Ea} \right) \tag{4}$$

Assuming that each center pivot (k) is assigned a single well in the irrigation scheme, then the seasonal well supply discharges $Q_{W(i)}$ in (m^3/season) from all the wells in the irrigation scheme serving all center pivots grown with crop (i) could be estimated as under:

$$Q_{W(i)} = GD_{(i)} \times Ncp_{(i)} \times \sum_{k=1}^{Ncp(i)} q_{W(k)} \tag{6}$$

Where,
$GD(i)$ = Numbers of growth days for crop (i)
$Ncp(i)$ =Number of center pivots grown with crop (i) in the irrigation scheme.
$q_W(k)$ = Well discharge (m^3/day) of well k, k=1 to $NCP(i)$

From equations 5 and 6 the seasonal over irrigation $Q_{O.I(i)}$ in (m^3/season) for any particular crop (i) in the irrigation scheme could be expressed as:

$$Q_{O.I(i)} = Q_{W(i)} - Q_{CWR(i)} \tag{7}$$

Identification of crop types and center pivot acreages

In order to identify crop types, the supervised classification was used (Saxena et al., 1992; Bingfang et al., 1994; De Jong and Burrough, 1995; Dymond et al., 1996; Saif ud din, 1999; Al-Rumikhani and Saif ud din, 2003). The Maximum Likelihood Classification was utilized because of its emphasis and ability to convert spectral classes into information classes from remote sensing data. The crop types were identified in the maximum likelihood classification image (Hall and Knapp, 1999; Saif ud din and Iqbaluddin, 1999; Siira et al., 1999; Haglund, 2000; Balaselvakumar and Saravanan, 2002). Different thematic elements were prepared for the supervised classification of the TM data training sets.

The Maximum Likelihood Classification makes use of the mean measurement vector M_c, for each class and covariance matrix for class c for bands k through i, V_c.

The classification rule states that:

$$X = C \tag{8}$$

If, $p_c \geq p_i$, where i=1,2,3,.......m possible classes

$p_c = \{-0.5 \log [\det (V_c)]\} - \{0.5 (X-M_c)^T (V_c^{-1}) (X-M_c)\}$

Where,

$\det (V_c)$ is the determinant of the covariance matrix (V_c).

To classify the measurement vector x of an unknown pixel into a class, the maximum likelihood decision rule computes the value p_c for each class. Then it assigns the pixel to the class that has the maximum value (Table - I). The classified crops are identified by correlation with training set collected from the field and later correlated with the rest of satellite image spectral data. The identified types of crops in the irrigation schemes (Tcrop). The routine will be assigned crop (i) to center pivot (k). The area of each crop (i) in center pivot k, $A_{(i, k)}$ is calculated. The same procedures will be repeated to obtain the acreage for each crop type in the irrigation scheme.

The developed methodology for estimating the regional irrigation water requirements was applied to Al-Busaita irrigation scheme, which is situated in Wadi As-Sirhan in Al- Jouf region North Western Saudi Arabia (Fig. 1). The remotely sensed Thematic Mapper (TM) data of Landsat-5 of Wadi As-Sirhan frame 172-039 of 15th March 2001 was employed in the analysis. The locations of the center pivots were identified and mapped with their corresponding areas from the digital data of Landsat TM. The training sets were collected from Al-Watania irrigation scheme and extrapolated to the entire region for the purposes of classification (Fig. 3). The Digital Image Processing (DIP) of the remotely sensed TM data was carried out using Intergraph's MGE Software and Microstation 95 CAD engine. The seven bands of the Thematic Mapper (having wavelengths 0.45 to 0.53, 0.52 to 0.60, 0.63 to 0.69, 0.76 to 0.90, 1.55 to 1.75, 2.08 to 2.35 and 10.4 to 12.5 µm respectively), ranging from visible to thermal infrared part of the spectrum were processed. The images were combined in the RGB format to create false color composites (FCC). Different FCC combinations were created i.e. 432, 734, 321, 456. The FCC's were interpreted using the photographic elements of shape, size, intensity, hue, saturation, texture and association to delineate the center pivots. The center pivots boundaries were digitized to calculate their acreages and stored as an overlay using the Microstation CAD software. The training data set consists of six data sets for crops, lithology and landuse in the area, which are agriculture 42.3%, rocks 20.15%, drainage channels 0.4%, stabilized sand cover 13.67, Aeolian dune sand 12.25, saline patch 2.42, besides 8.81% unknown classes.

The crop factor (Kc) values for each growth stage, for the major crops in the irrigation scheme, were taken from the published report of the Ministry of Agriculture and Water (Nimah et al., 1986) as shown in (Fig. 2a). The average crop growth stage water requirements are shown in Fig. 2b. All crops except alfalfa, which is a perennial crop, are seasonal. The Alfalfa crop usually has ten cuttings cycles per annum, and the Kc value after each cutting cycle returns to the initial Kc (Allen et al., 1998; Anon, 2001; Kizer, 2000). The weather data were acquired from the weather station Dawmat Al- Jandal, which is adjacent to the irrigation scheme (Fig. 1). Ten-year averages (1990 to 2001) of weather data was used to calculate grass reference evapotranspiration (ET_O). The weather database with variables such as air temperature (minimum), air temperature (maximum), relative humidity, solar radiation, sunshine hour and wind speed was used to generate the weather information

Results and discussion

A total of 2505 center pivots in the irrigation scheme were identified with different dimensions covering a total cultivated area of 104814.88. The green colored circular fields characterized alfalfa, blue were potato fields, yellow were tomato fields, wheat field were red in color (Fig. 3). The magenta colored patches in geometrical shapes and brown were identified as plantations and uncultivated fields respectively. The basalts were characterized by dark yellowish green color in northeastern part of the image and carbonate rocks by brownish green color in Southwestern part of the scene. The paleo-channels and the active drainage channels were identified as dark green colored and light green colored respectively. The high moisture area is having bright pink color; the stabilized sand is dark colored, while the Aeolian sand cover is greenish brown. The saline patch is blue colored (Fig. 3). The total agriculture cover is classified into alfalfa 75%, potatoes 5%, tomato 3% and wheat 5%, Plantation 1.37, uncultivated fallow 10.63%. The rocks were classified into Basalts 25.757% and carbonates 74.243%. The statically data (Table - I) shows twelve classes covering 91.19% of pixels with 8.81 % were classified as unknown classes. The spectral signatures of the twelve classes in seven bands are given in Fig. 4. There are about 13 soil associations in the study area. But the majority of the center pivots are localized in three soil types. In the maximum likelihood classification image (Fig. 3) twelve classes were identified as alfalfa, potatoes, tomatoes, wheat, plantation/orchards and uncultivated agricultural fallow, hard rock (Basalt and Carbonate), sand (stabilized and Aeolian dunes), drainage channels and Saline patch (Sabkha). Irrigated crop acreage was calculated based on image interpretation. The interpretation revealed that, the total agricultural landuse was 104814.88 ha, the cultivated acreage was 91188.88 ha , the under plantation acreage was 1345 and the uncultivated center pivot acreage was 12190 ha.

The durations of the growth stages of the four major crops are given in Table – II. The total crop water requirement was calculated for alfalfa, potato, wheat and tomato crop (Table – III). The irrigation scheduling efficiency for different soil associations were computed from stage wise crop coefficients (Anon, 2001).

The average individual wells yields in the irrigation scheme range from 8208 to - 13680 m^3/day. However, the existing irrigation practices in the irrigated schemes, in most cases, is that the center pivots are operated for 18 hours/day and switched off three days before crop harvest (cutting). Assuming an average well discharge of 10000 m^3/day, for single wells serving individual center pivots, Table – IV presents the monthly and total crop water requirement and estimated over irrigation for the four major crops grown in Al- Busaita irrigation scheme. The presented data in Table –IV-A shows that, there are 1875 center pivots comprising 78611.16hectare grown with alfalfa in the irrigation scheme. The estimated irrigation water requirements throughout the growing season is 34900.84 m^3/ha/ season This correspond to a total irrigation water requirements of 2743.3 million m3/ season (12 months). The total wells discharge for the center pivots grown with Alfalfa in the irrigation scheme is 6843.75 million m^3/season. Most of the over irrigation occurs in the winter months due to the low evapotranspiration rate as compared to summer season. For example, the over irrigation reduces from about 510 million m^3 in January to 186 in July. On seasonal basis the over irrigation is estimated at 4100 million m^3/season.

The Wheat crop is grown in 100 center pivots comprising about 4192.58 hectares as shown in Fig IV- B. The estimated seasonal (5 months) irrigation water requirements per hectare are 6316 m^3. This corresponds to a total estimated irrigation water requirement of 26.5 million m3/ season, resulting in an e estimated over irrigation of about 103 million m3/ season. There are 125 center pivots grown with the Potatoes crop comprising an area of about 5240 hectares in the irrigation scheme. The estimated seasonal irrigation water requirements (5 months) per hectare are 6582 m^3, corresponding to a total estimated irrigation water requirements of 34.5 million m3/ season. The estimated over irrigation about 104 million m3/ season. Finally, 75 center pivots were recognized as grown with the Tomatoes crop comprising an area of about 3144.45 hectares in the irrigation scheme. The estimated seasonal irrigation water requirements (4 months) per hectare are 8323 m3. The total estimated irrigation water requirements were estimated to about 26.2 million m3/ season. The estimated over irrigation was estimated as 48.8 million m3/ season. The slight decrease in over irrigation could be attributed to the fact that part of the tomatoes growth period occurs in the months of April and May, which are relatively hot in the irrigation scheme.

Conclusion

The study which was carried out using remote sensing technology is effective in agriculture mapping and irrigation water conservation monitoring. The supervised classification was carried out based on the training set data collected from part of the study area. The accuracy in quantifying crop irrigation water requirements, which is obtained with the help of remote sensing technology and interpretation, is acceptable for region scale investigations. The study demonstrated a huge percentage of over irrigation, due to the improper estimation of irrigation water requirements. However, irrigated agriculture in arid lands needs proper water resource management to eliminate over irrigation. For example, the observed changes in center pivots acreage, by reducing the center pivot length while keeping fixed well discharge has significantly contributed to the problem of over irrigation. Furthermore, the irrigation through exploitation of fossil ground water can be optimized through increase in irrigation frequency and decrease in amount of water used in each irrigation cycle, resulting in ground water conservation in arid ecosystems. The study suggests that exact crop water requirement should be estimated and irrigation application be planned accordingly, for ground water conservation without reducing the crop yields. The present research confirmed that, the interpreted results from remote sensing can be effectively integrated with the crop water requirements models for planning proper irrigation scheduling i. e. duration of irrigation, amount of irrigation required, etc., through crop identification, acreage and growth stage evaluation using real time remotely sensed data in the arid lands. Moreover, a much better utilization of the irrigation water resources could be achieved by adjusting the duration of center pivot well pumpage and speed of center pivot as per the stage wise crop water requirement; so as to minimize over irrigation. This would mean that, individual wells in the irrigation scheme could be utilized to serve more than one center pivot. This could reduce the estimated crop water requirements by at least 50% without compromising the crop yield.

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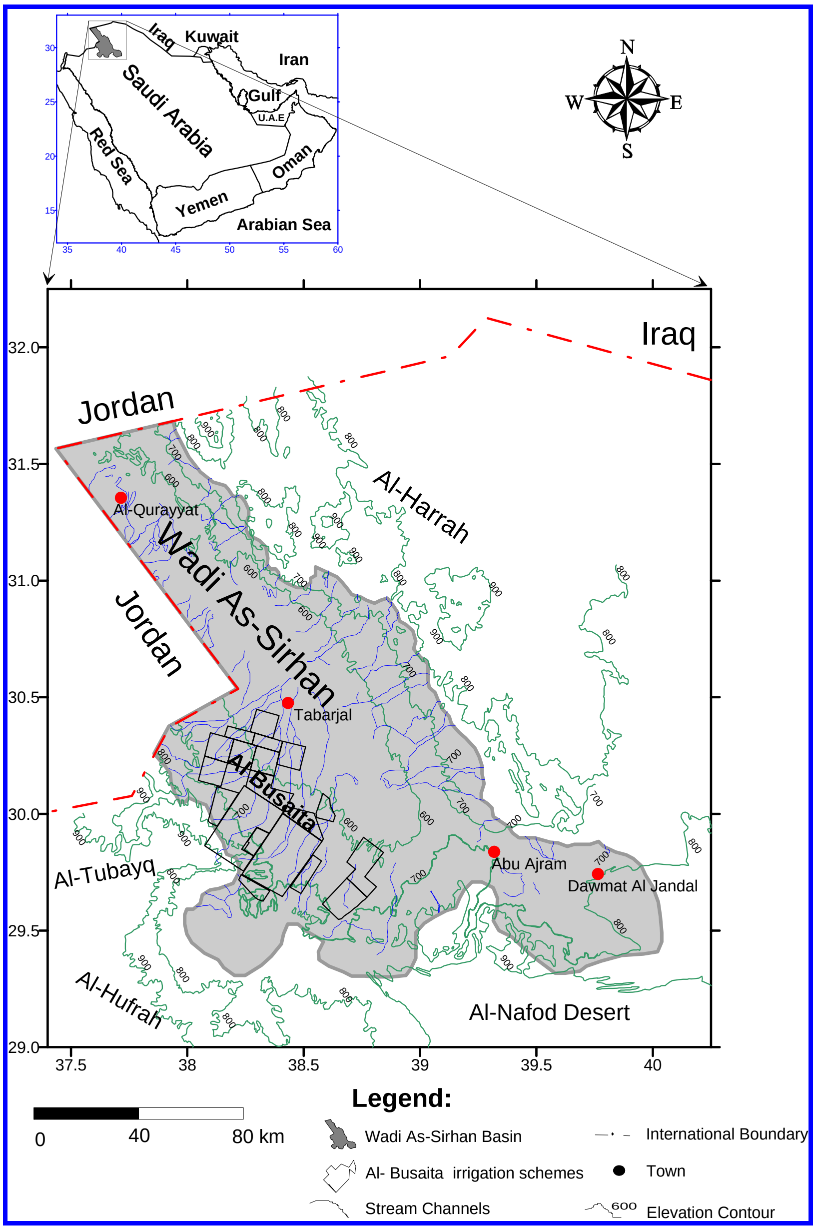

Fig. 1. Location Map of Al-Busaita irrigation scheme North-West Saudi Arabia

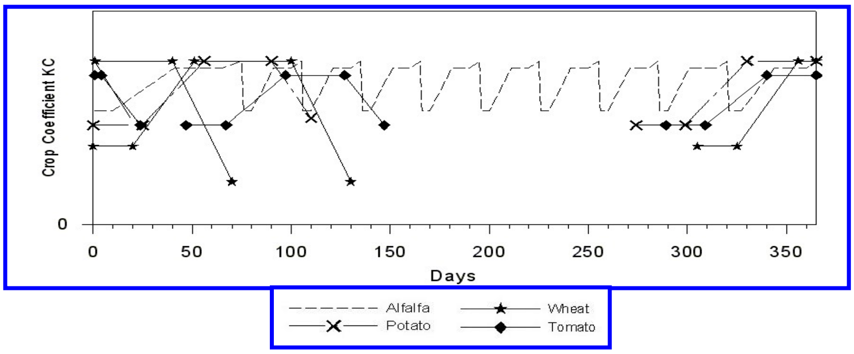

Fig. 2a. Growth Stage wise crop coefficient values for the major crops grown in Al – Busaita irrigation scheme

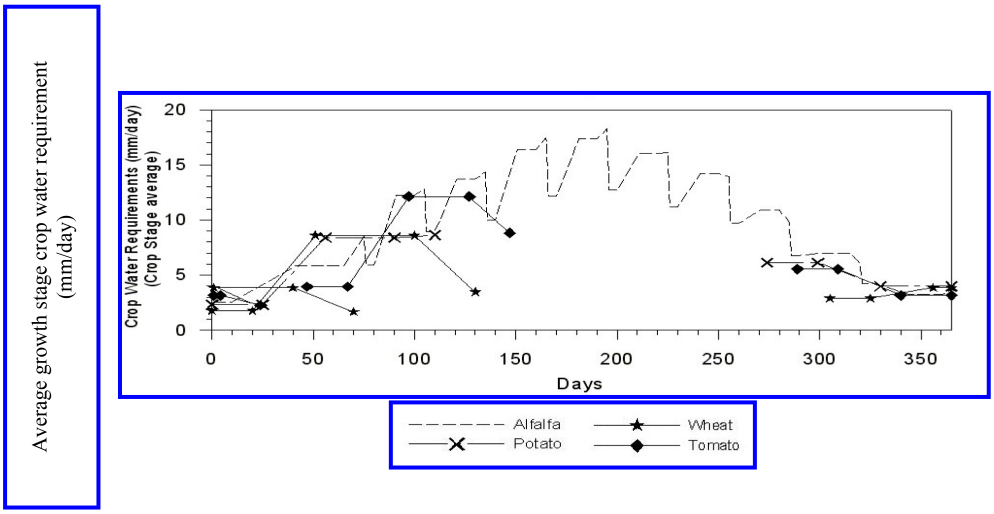

Fig. 2b. Growth Stage wise Crop water Requirement of Major Crops grown in Al – Busaita irrigation scheme

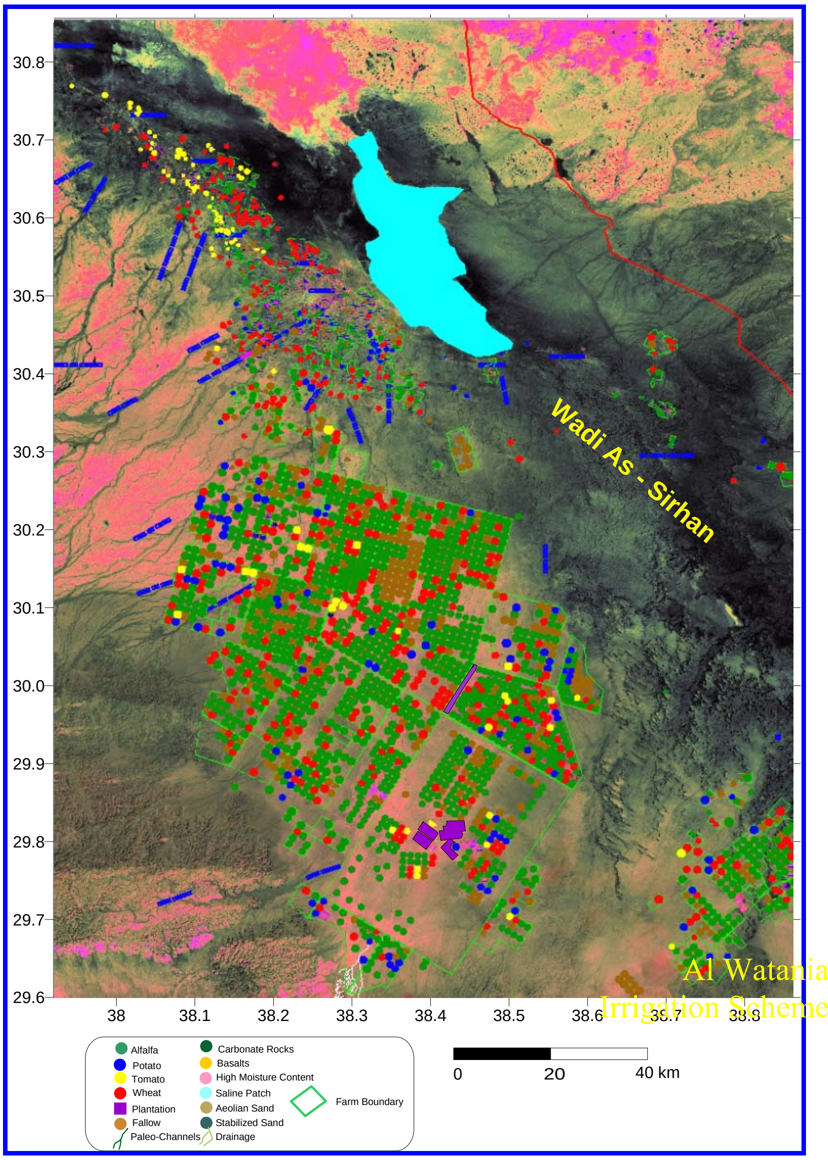

Fig. 3. Maximum Likelihood Classified Image of Band 432, path row 172-039 of 15th March, 2001

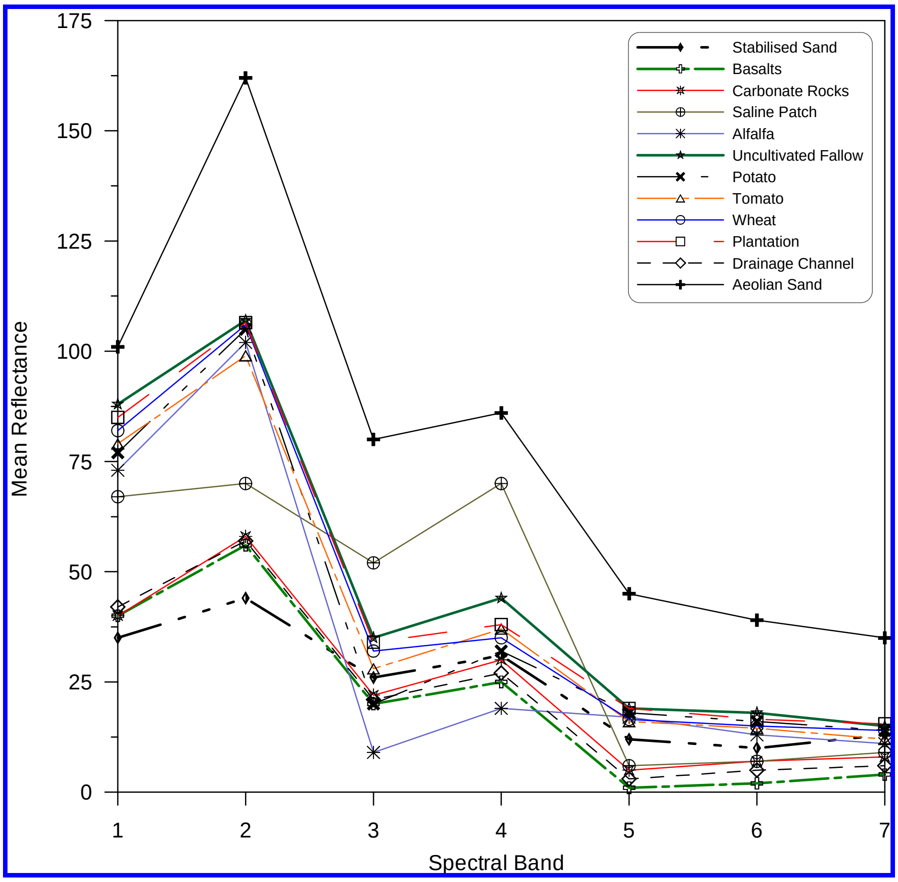

Fig 4. The Mean Spectral Reflectance of twelve classes in each band

Table I. The Classified clusters in the Landsat Image of the Study area

Cluster Name	Frequency
Alfalfa	35744761
Potato	2382984
Tomato	1429790
Wheat	2382984
Plantation	652938
Uncultivated Fallow	5066224
Carbonate Rocks	16853444
Basalta	5847646
Drainage	450683
Stabilized Sand Cover	15402076
Aeolian Sand Dune	13802153
Saline Patch	2726630

Table2. Duration of growth stage for crops

Crop	Growth stage 1 in days	Growth stage 2 in days	Growth stage 3 in days	Growth stage 4 in days
Alfalfa 1st cutting cycle	10	30	25	10
Alfalfa subsequent cutting cycles	5	10	10	5
Potato	25	30	35	20
Tomato	20	30	30	20
Wheat	20	30	50	30

Table 3. Total Crop Water Requirement

S.No.	Crop	Season	Total Crop Water Requirement in m^3/ha/season
1.	Alfalfa	January – December	34864.00
2.	Potato	January – April	6522.00
3.	Potato	October – January	5160.00
4.	Wheat	November – February	3724.00
5.	Wheat	January – April	6473.00
6.	Tomato	October – January	3792.00
7.	Tomato	February – May	8296.00

Table 4. Irrigation water requirements and over irrigation for the four major crops in Al-Busaita ittigation scheme (One well for one center pivot system)

A - Alfalfa (Sowing Date: 1 Jan.), Growth period: 365 days — Total number of center pivots grown with Alfalfa = 1875, Total Cultivated Area (ha) = 78611.16

Months / No. of sowing days / month	Jan 31	Feb 28	Mar 31	Apr 30	May 31	Jun 30	Jul 31	Aug 31	Sep 30	Oct 31	Nov 30	Dec 31	Total	Unit
Estimated irrigation water requirements (m^3/ha/month)	905	1,378	2,196	3,401	3,918	4,630	5,021	4,423	3,701	2,677	1,609	1,042	34,901	m^3/ha/ season
Total estimated irrigation water requirements/ total acreages area in the irrigation scheme (million m^3/month)	71.1	108.3	172.6	267.4	308.0	364.0	394.7	347.7	290.9	210.4	126.5	81.9	2,743.6	million m^3/season
Total well discharge for the total Cultivated Area @10,000 m3/day (million m^3/day)	581.3	525.0	581.3	562.5	581.3	562.5	581.3	581.3	562.5	581.3	562.5	581.3	6,843.8	million m^3/season
Over Irrigation (million m^3/month)	510.1	416.7	408.6	295.1	273.2	198.5	186.6	233.5	271.6	370.8	436.0	499.3	4,100.2	million m^3/season

B - Wheat (Sowing Date: 15 November), Growth period: 130 days — Total number of center pivots grown with Wheat = 100, Total Cultivated Area (ha) = 4192.59

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Unit
No. of sowing days in month	31	28	25	0	0	0	0	0	0	0	15	31		
Estimated irrigation water requirements (m^3/ha/month)	1,939	2,327	580	0	0	0	0	0	0	0	287	1,183	6,316	m^3/ha/ season
Total estimated irrigation water requirements/ total acreages area in the irrigation scheme (million m^3/month)	8.1	9.8	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	5.0	26.5	million m^3/season
Total well discharge for the total Cultivated Area @10,000 m3/day (million m^3/day)	31.0	28.0	25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0	31.0	130.0	million m^3/season
Over Irrigation (million m^3/month)	22.9	18.2	22.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	26.0	103.5	million m^3/season

C - Potato (Sowing Date: 1 Jan.), Growth period: 110 days — Total number of center pivots grown with Potato = 126, Total Cultivated Area (ha) = 5240.74

Months / No. of sowing days in month	Jan 30	Feb 28	Mar 31	Apr 21	May 0	Jun 0	Jul 0	Aug 0	Sep 0	Oct 0	Nov 0	Dec 0	Total	Unit
Estimated irrigation water requirements (m^3/ha/month)	1,069	1,890	2,672	951	0	0	0	0	0	0	0	0	6,582	m^3/ha/season
Total estimated irrigation water requirements/ total acreages area in the irrigation scheme (million m^3/month)	5.6	9.9	14.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.5	million m^3/season
Total well discharge for the total Cultivated Area @10,000 m3/day (million m^3/day)	37.8	35.3	39.1	26.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	138.6	million m^3/season
Over Irrigation (million m^3/month)	32.2	25.4	25.1	21.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	104.1	million m^3/season

D - Tomato (Sowing Date: 15 Feb.), Growth period: 100 days — Total number of center pivots grown with Tomato = 75, Total Cultivated Area (ha) = 3144.45

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Unit
No. of sowing days in month	0	13	31	30	26	0	0	0	0	0	0	0		
Estimated irrigation water requirements (m^3/ha/month)	0	794	2,105	3,652	1,772	0	0	0	0	0	0	0	8,323	m^3/ha/season
Total estimated irrigation water requirements/ total acreages area in the irrigation scheme (million m^3/month)	0.0	2.5	6.6	11.5	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.2	million m^3/season
Total well discharge for the total Cultivated Area @10,000 m3/day (million m^3/day)	0.0	9.8	23.3	22.5	19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.0	million m^3/season
Over Irrigation (million m^3/month)	0.0	7.3	16.6	11.0	13.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	48.8	million m^3/season